Mixed-Initiative Remote Characterization Using a Distributed Team of Small Robots

David J. Bruemmer
Donald D. Dudenhoeffer
Julie L. Marble, Ph.D.
The Human-System Simulation Laboratory
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3779, U.S.A.

Abstract

Using a team of small, sensor-rich robots and a larger, Parent robot, we have explored the problem of how to enable flexible, adjustable autonomy control for a multi-robot remote characterization task. To accomplish the task, the robot team must autonomously deploy into a building, efficiently search through corridors and rooms to locate a spill, and then cooperatively form a perimeter around a chemical spill, once found. The system should be able to accomplish these objectives with human input varying from complete to none at all. We have developed a graphical user interface (GUI) that allows hierarchical tasking for groups of robots and have married this software to individual robot behaviors and a multi-modal communication architecture comprised of radio, infrared, and audible chirping. The ability for the robots to chirp and respond to chirps is the basis for our implementation of social potential fields – attractive and repulsive forces that can promote grouping behaviors between adjacent entities such as might be seen in a flock of birds or a school of fish. Through coverage experiments in a test-bed environment, we have found that social potential fields provide a means to control a variety of emergent swarm effects including swarm size, swarm density, swarm translation. As this paper will discuss, social potential fields provide a unique means to accomplish deployment, convergence to the spill and to orchestrate perimeter formation.

Introduction

The objective of this project has been to develop and evaluate command and control (C2) architectures that permit deployment and operational tasking of many small to mid-sized robots. The problem of creating coordinated social behavior from simple, reactive behavior sets is not easily solved. In previous work the Idaho National Engineering and Environmental Laboratory (INEEL) has developed and tested C2 architectures using computer simulation. More recently, our goals have been to port the resulting C2 architecture onto a collective of cost-effective, small, mobile robots and to address real-world issues surrounding deployment and tasking.

For large numbers of robots to be deployed as viable force, human users must be able to interact with functional units – strategic groupings of robots – rather than issuing commands to each individual robot. Rather than making the user exert global, centralized control from above, this project has developed individual robot behaviors that can promote the emergence of swarm intelligence, as seen in a colony of ants or swarm of bees. While the focus of the project is on collective performance, each individual robot acts in a fully distributed, autonomous fashion using highly robust suites of sensors and behaviors. To enable useful group behavior, the INEEL has developed an innovative, multi-modal communication architecture consisting of acoustical chirping, infrared and radio frequency (RF) communications. At the highest level, a C2 software tool has been developed that enables an operator to inject domain knowledge and guidance into the behavior of the otherwise autonomous system. The objective of the C2 system is not only to provide a means of task dissemination, but also to facilitate mission planning, re-tasking, and operator understanding.

Using the real-world robot collective and C2 system the INEEL has performed experiments to empirically analyze the benefits and limitations associated with the use of small-scale, multi-robot systems. These experiments also have demonstrated a spill finding and perimeter-formation operational scenario. Throughout this effort, significant effort has centered on quantifying the benefits of distributed robot teams for select Department of Energy and Department of Defense missions, and to examine mission shaping factors for deployment scenarios.

Research Issues

Despite significant work over the last decade, challenging problems inherent to designing and deploying large numbers of real robots remain, including among other issues, positioning (i.e., giving each robot a knowledge of where it is), communication (both between robots, robot to operator, and between operators), and power. In order to move into a new, truly distributed paradigm, these problems cannot be addressed using sensors and platforms that emphasize the capabilities and intelligence of the individual. One intriguing solution is the creation of emergent insect-like behaviors to increase the autonomy of the robot.

The environment perceived by large robots using sonar, laser range finders, stereo range cameras or computer vision is of an utterly different sort than the percepts available to insects. Range sensors are more precise and discrete but are also limited in scope for the very reason that they hone in on a finely cut slice of the environment. Although computer vision offers a seemingly infinite richness, it is inappropriate for a highly reactive system and intractable in terms of processing.

Despite their processing limitations, insects do not suffer from a paucity of data; rather they are inundated by a kind of sensor data that is rich precisely because it is desultory and without scope. Insects capitalize on the fact that significant environmental events will most likely produce a light or sound fluctuation. A sudden change in light can speak volumes. Such a qualitative change, then, is more telling than a purely quantitative range. However, although very little goes wholly unnoticed by insects, there is typically no connection made by the insect between the causal event and the resulting sensations. Although insects sense environmental stimuli, they do not form perceptions. Insects have sacrificed comprehension for more adept powers of apprehension and in so doing have become masters over a chaotic world of light and sound gradients for the most part unnoticed by the human senses.

Early in our project, simulation of large-scale robot interaction offered key insight, but ultimately could not provide the fertile soil of chaotic, real-world physics necessary for swarm intelligence to reap its full rewards. In an attempt to move closer toward this form of organic, indiscriminant sensing, the INEEL uses touch sensors, photo-resistors, microphones, and IR sensors, all of which allow a tight coupling between sensing and action. Within this embodied approach, the robots learn to respond appropriately to fluctuations in sound and light; in fact, obstacle avoidance and a variety of social behaviors including searching, spill convergence, and, perimeter formation are all dependent on the robot's ability to both recognize and instigate these fluctuations. While this paradigm offers great dividends in terms of scalability, robustness, domain-generality, and decentralization, it does not come without a price. Small variations in the placement and sensitivity of the robot's sensors and actuators can result in overwhelming effects, often evident as unpredictable behaviors based on the stigmergy-mediated, compounding interactions between robots.

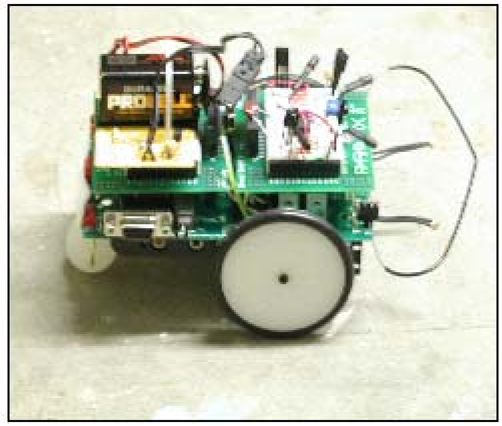

Figure 1. GrowBot instrumented with microphones, spill sensor, infrared, bump, and light sensors

Despite the development challenges, we believe that to enable large numbers of small robots to be successfully deployed, we must have control architectures, robot platforms and sensors that can scale easily in terms of cost, size, computation, and bandwidth. Rather than rely on the crutches of global control, significant processing power, accurate position information, or reliable, explicit communication architectures, we promote the emergence of fully decentralized swarm intelligence whereby many simple agents generate patterns and self-organize through nearest-neighbor interactions.

One means that insect societies use to impose order and structure onto the otherwise erratic behavior of individuals is group formation behavior where a spatial relationship is maintained implicitly between adjacent entities, as in a flock of birds, a school of fish, or a swarm of gnats. Likewise, we have found that social potential fields (Dudenhoeffer & Jones, 2000; Reif & Wang, 1999) provide a means to control a variety of emergent swarm effects such as swarm size, swarm density, swarm translation, and the propensity of the swarm to explore new ground. Our work with a collective of 12 small robots shows that social potential fields, although wrought entirely through local interactions and reactive behaviors, can provide a means for global coordination and control of a collective as it performs searches in various environments. We have also shown that by modulating these fields through online adaptation or in response to high-level user commands, it is possible to spur dramatic performance improvements in the behavior of the collective (Dudenhoeffer and Bruemmer, 2001).

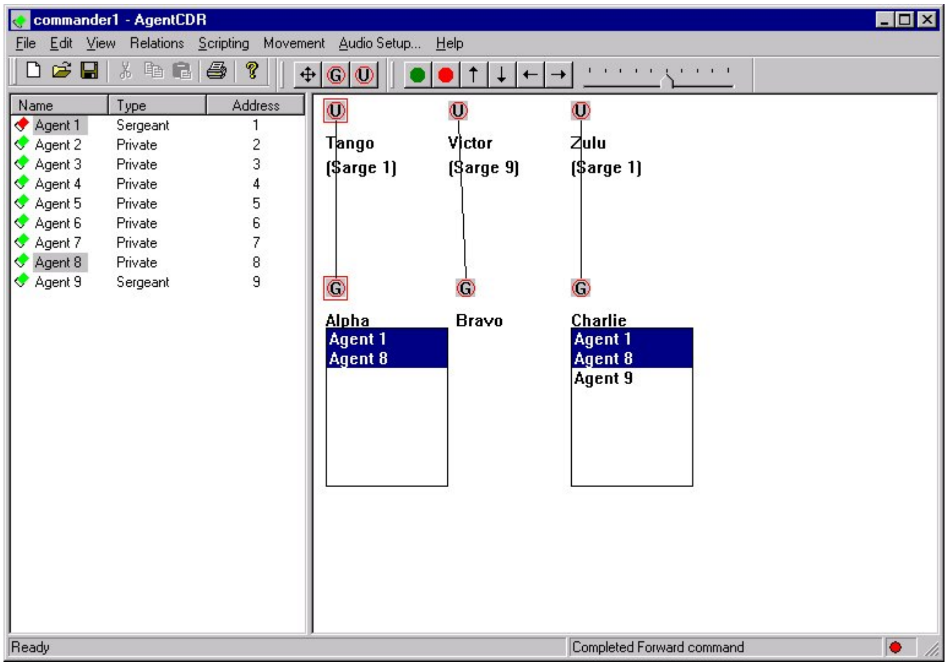

Figure 3. AgentCDR in control of nine robots. Assets are partitioned into three groups governed by two sergeant robots. A sergeant may control multiple groups and membership between groups may overlap. The window at the left lists all available resources

Social Potential Field Implementation

The test platform chosen for this research project was the Growbot™ by Parallax. We have significantly modified the platform, adding modules for spill detection, infrared (IR) communication, IR obstacle avoidance, and chirping. Compared to larger robots, the Growbot™ is extremely limited in capability. This was a deliberate research choice and a research challenge, to create a powerful collective of individually diminutive robots. Figure 1 shows one of our robots in a basic configuration with a moisture detection sensor, bump sensor, two whisker-like light sensors, four IR sensors for obstacle avoidance, a ring of IR for local communications, a piezoelectric speaker and two directional hearing aid microphones, one in the front and one in the rear. The robot collective includes sergeant robots that are specialized for communication. Radio frequency transmission capabilities allow the sergeants to receive commands from a human operator. The sergeants then use IR transmission to disseminate these commands to the privates.

The INEEL has implemented social potential fields on a collection of 12 robots using a combination of IR obstacle avoidance, light sensing and audible chirping. The effect is that each robot exerts both an attractive and repulsive force field. The attractive field, based primarily on sound, can either can discourage robots from moving too far away (an essential aspect of stable swarming behavior) or can actively pull other robots towards itself as in the case of the "come hither" chirp emitted by a robot that has found an area of interest, such as a spill. The repulsive field discourages robots from coming too close and is comprised of sound (robots avoid chirps above a certain volume) and the various obstacle avoidance sensors, which include infrared, light sensing, and bump sensing as a last resort.

Social potential fields provide a basis for online adaptation. By adjusting these fields based on bumps and turn frequency, the robots can automatically adapt themselves to various environments and changing swarm densities. We believe such an approach is uniquely appropriate for distributed systems especially as we scale towards large numbers of very small-scale, resource constrained robots. For one thing, the sensors involved make minimal demands of cost, size, and processing power. In addition, this intrinsic means of behavior modulation system can permit a user to control swarming behavior at a high, abstract level. Most importantly, it provides the swarm with a means to automatically regulate itself. By displacing elements of command, control and communication onto the environment, our implementation of social potential fields enables:

- Self-organizing, self-regulating cooperative behavior;
- Online learning and adaptation;
- Emergent intelligence;
- Flexible autonomy;
- Implicit communication.

Through these advantages, our embodied use of social potential fields seems to bring us closer to the insect world. However, adopting this paradigm does not come without a price. Individual robot behavior, much like the behavior of an individual ant, is difficult if not impossible to predict. The need to debug and task these simple robots presents an especially difficult challenge, since individually the robots are unable to communicate meaningfully with the operator.

Command and Control

Unlike the insect world, the robotic system must interact with human operators. At a minimum, this interaction includes responding to operator directed tasking and providing status reports on task progress. Ideally, the user should not be required to task individuals, but should be able to abstract group command and control functions. To support this need for high-level command and control, INEEL has developed a hierarchical communication architecture where sergeant robots, specialized for communication, receive commands from the user. The sergeant robots then disseminate commands to the "privates" under their authority. This is done implicitly using a combination of IR communications and acoustic chirping. To utilize these capabilities, INEEL has developed a suite of command and control software called ***AgentTools*** that facilitates planning, online tasking and mission control over the robot collective.

The AgentTools architecture, shown in Figure 2, includes a suite of modular command and control tools. AgentSim provides systems simulation. AgentCentral (still under construction) provides a central command station for all infield units. AgentCDR is an operator control unit for interacting with and deploying robotic forces. AgentCDR offers a means to modulate swarm behavior by issuing high-level aggregation/dispersion commands and yields advanced C2 support, which includes additional human-centric visualization tools, iconographic representation of robots, GUI controlled group assignment, operation planning tools, and system status alerts for communication failure. However, the privates are not dependent on the sergeants or on the human operator for continuous communication and can function autonomously in the absence of sergeant or user input. This flexibility supports mixed initiative control and allows AgentCDR to balance the needs and limitations of the robots, C2 structure, and the human operator(s).

One of the issues in utilizing small robots is control of their initial placement within the environment. To face this deployment problem, INEEL has developed a Parent robot that can deploy the robots by emitting a "follow me" chirp. In turn the smaller robots utilize a combination of an IR-based follow behavior and a sound-based chirp follow behavior to track the Parent. Figure 4 illustrates the Parent robot, an ATRVJr., leading a group of smaller robots.

The Parent robot not only deploys the robots into a building, but can also assume a monitoring mode. Each sergeant has a different color that the Parent robot uses to visually distinguish the sergeant from the other robots and track its movement. Using this tracking behavior, the Parent can provide visual feedback on a particular group by following a certain distance behind a specified sergeant. In terms of the operational scenario, the ability to autonomously provide visual feedback is a crucial form of support for the operator using AgentCDR. In this scenario, the Parent uses its vision system to autonomously follow the sergeant. Figure 5 shows the view from the Parent robot's camera. This is the view that the operator sees while remotely operating the robots.

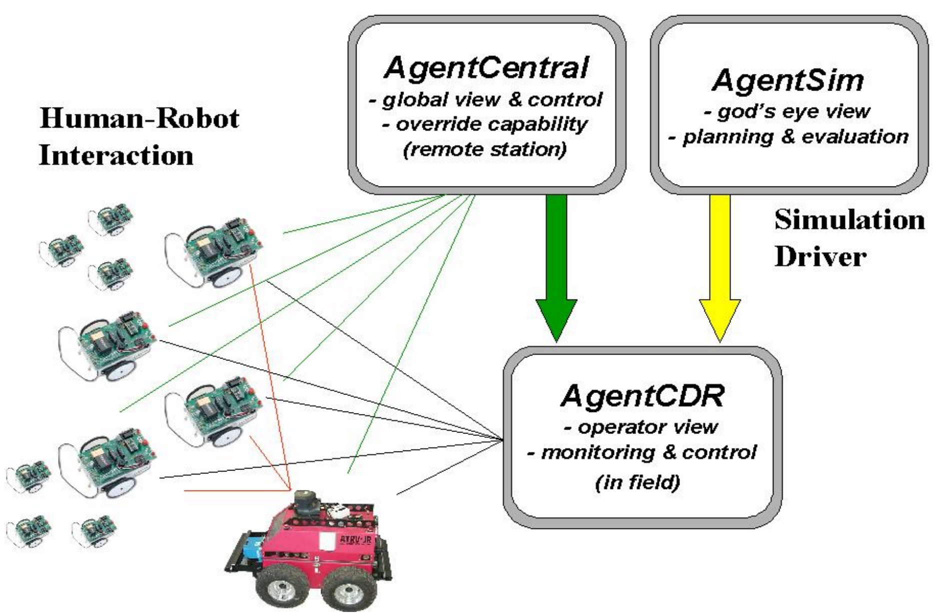

Figure 2. AgentTools -- A suite of command and control software tools

Figure 4. The Parent robot deploys the smaller robots through a doorway into a large DOE facility.

Figure 5. A video stream of the Growbots taken from a sensor on the ATRVJr.

Throughout a recent mock deployment of the system in a DOE building, the ability for the Parent to autonomously track and provide visual feedback on the swarm behavior allowed the user to accomplish difficult tasks, for example, guiding a group of robots through a door and into a new area of the building. Rather than adding complexity to the task, the Parent robot's ability to autonomously provide visual feedback alleviated cognitive load for the operator and augmented the utility of the robot swarm.

Perimeter Formation

At the 2001 AAAI Conference in Seattle, WA, the INEEL demonstrated the ability of a team of seven robots to locate and form a perimeter around a water spill using ambient chirping as a means to initiate convergence to the spill and orchestrate the formation of a perimeter around it. This behavior was demonstrated both within the NIST Urban Search and Rescue test bed and within an exhibition arena. After release, the robots began to disperse using their social potential fields to implicitly divide the environment.

The social potential fields adjust automatically based on the robot's experiences. As the robots find themselves surrounded by varying densities of obstacles or other robots, they automatically adjust a triumvirate of light-sensitivity, turn gain, and average turn frequency. Raising these parameters causes the robots to become more responsive to their environment, maintain a tighter social potential field, and become less likely to explore new ground. By lowering these parameters, the social potential field effect decreases, and therefore the robots become more likely to venture out and cover new ground. This online adaptation refines and filters the randomness streaming in from the environment and helps to avoid the "chattering" effect whereby robots waste time by spinning in place as they attend to each tiny change in the environment.

The length of time necessary for the first robot to locate and identify the spill differed significantly during the tests, since the robots initially perform a random search. Once one robot found the spill and began to emit an audible signal, congregation and perimeter formation occurred quickly as the other robots were drawn to the "come hither" chirp. Although the "come hither" chirp exerted a definite influence on the other robots, this influence could be temporarily subsumed by higher priority behaviors invoked by the presence of other robots, static obstacles, and even by shadows thrown by onlookers.

Furthermore, the convergence behavior itself was susceptible to the acoustics of certain environmental areas and by the diverse noises coming from other areas of the exhibition hall. Although the convergence behavior would inevitably prevail, it was not optimal. This was the price to be paid for using fully distributed control and implicit communication. For instance, a robot would often be drawn to the spill by the "come hither" chirp, only to be turned away at the last moment by the repulsive arm of the social potential fields of the robots already on the spill. At first, we removed this repulsive field in order to expedite convergence to the spill, but found that we had lost our means to distribute the robots evenly around the spill perimeter. With the repulsive field in place, an incoming robot would be forced away by the robots already on the spill and must eventually find its own place to roost along a less populated stretch of the spill perimeter. In this manner, we were able to accomplish perimeter formation in an entirely reactive manner. No explicit algorithm was necessary, thereby reducing the need for on-board processing and eliminating the need for explicit communication and centralized control.

While the robots were consistently able to find and form a perimeter around the spill(s), this behavior was by no means immediate, or accomplished in a precise or even consistent manner. The robots receive a high degree of random data from the environment in the form of light and sound fluctuations. Even the noise of the robots' wheels and the shadows they cast affect the behavior of the robots. Moreover, the use of online adaptation means that although the robots all begin with the same program, each robot soon acquires a unique sensitivity based on its own experiences. In fact, simply by observing the robots, onlookers could ascertain that certain robots seemed "braver" or more "timid" than did others. This diversity can be useful in ensuring coverage over a large, varied area. However, it also makes it difficult to predict exactly how a particular perimeter formation scenario will unfold.

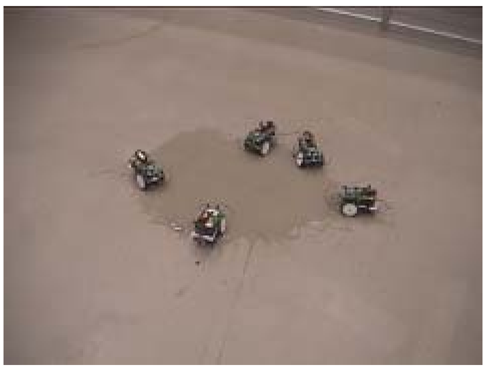

Figure 6. Five robots have formed a perimeter around a water spill.

Over the course of these experiments, we witnessed some interesting effects evolving from the implicit interactions of the individual robots. Due to the additive properties of sound, the attractive force of the robots that have already found the spill extends as more robots find it. This provides a rudimentary form of peer validation. If a robot mistakenly identifies a plume, the attractive force will remain small since other robots will not augment the sound. One effect that we had not expected was that the repulsive arm of the social potential fields also grew as robots began to form a perimeter, making it increasingly difficult for each additional robot to get onto the spill. When two separate small spills were used, the combined repulsive field of the robots that had already formed a perimeter around the first spill prevented excess robotic resources being spent on the already marked spill. Instead, the strong repulsive arm pushed the remaining robots away from the first spill, allowing them to seek out the second. In contrast, when there was only one large spill, all the robots were able to find a place around the perimeter of the spill; the repulsive arm extended only far enough to force robots around the perimeter. Figure 6 illustrates a group of robots surrounding a spill.

Conclusions and Future Work

By creating a system that, like insects, is sensitive to a thick slice of environmental physics, we increase the domain-generality and robustness of our robots; but, similarly, we must sacrifice almost all hope for unerring resolution on the part of the robots. Perhaps the more we incorporate insight drawn from the insect world, the more willing we must be to accept insect-like limitations. Individuals may demonstrate unexpected, although explainable, behaviors due to these limitations. Although entomologists can observe and record definite trends in insect behavior, it is not necessarily the case that a particular ant will follow this trend. Likewise, with our experiments, we found it necessary to focus on group success rather than worry about the behavior of an ostensibly errant individual as it navigates a world of light and sound gradients undetectable to human senses.

In the future, the INEEL will investigate how to go beyond problems of laboratory implementation to face the fundamental issue of how to create a usable application. Currently, the INEEL is working toward a full-fledged operational scenario where the robots will be deployed by a larger robot into a hazardous environment. To this end, the INEEL has demonstrated that AgentCDR can effectively deploy and task a team of cost-effective, small robots to find and converge upon a mock 'spill' within a DOE regulated facility at the INEEL.

We envision the robotics technologies developed in our research being used to map and characterize buried waste sites and retired facilities, to perform routine inspection and monitoring of critical components, to perform environmental monitoring and building surveillance appropriate for DOE long term stewardship needs, and to provide rapid response remote characterization capabilities in the event of a hazardous spill or radiation leak. Small scale distributed robot systems, such as the one discussed in this paper, can reduce cost, remove workers from the dangers of radioactive or hazardous materials, and increase productivity by accomplishing slow painstaking tasks. Paramount to realizing these benefits is the construction of robust robot behaviors tightly coupled with human operator interface systems, which promote system understanding and facilitate human interaction.

References

Dudenhoeffer, D. D., & Bruemmer, D. J. 2001. Command and control architectures for autonomous micro-robotic forces. INEEL/EXT-2001-00232, Idaho

National Engineering and Environmental Laboratory, Idaho Falls, ID.

Dudenhoeffer, D. D., & Jones, M. P. 2000. A formation behavior for large-scale micro-robot force deployment. In J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick (Eds.), *Proceedings of the 2000 Winter Simulation Conference*, (pp. 972-983), Orlando, Florida: Institute of Electrical and Electronics Engineers.

Reif, J. H., & Wang, H. 1999. Social potential fields: A distributed behavioral control for autonomous robots. *Robotics and Autonomous Systems, 27*, 171-194.